

COST EFFECTIVE ULTRA LIGHT WEIGHT MIRRORS

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ABSTRACT

The replication technique by nickel electroforming is a well known technology used to obtain thin, lightweight and very precise mirrors for X-rays in such projects as SAX and JET-X and XMM. Previously published data has shown that these three projects have demonstrated the progressive development of the technology. The practicality of making further advances in this technology has now been demonstrated by very significant reductions in the thickness and consequent weight of these type of X-ray mirror shells. Results have demonstrated that this has been achieved without degradation of the mirror optical quality and that this technique is still far from fully exploited.

Further developments have advanced this production technique to a level at which it is possible to produce much larger structures of very different shapes from the original Wolter I and double cone shell. The possibilities of this process are numerous and various types, including off axis mirrors have now been produced. Depending on the final application these mirrors can be used as produced; can be increased in stiffness by the use of other technologies such as composites and sandwich structures; or can be made more flexible for use in adaptive systems.

Major additional benefits can be achieved by the use of this type of replication technology, such as the production many identical mirrors from one relatively small master that can then be assembled together to form a segmented, axis symmetrical reflector or used to form deployable systems. The use of metals for large reflectors can be advantageous due to the extremely predictable physical properties and well documented life span, the nature of these properties will be discussed.

1. INTRODUCTION

Nickel technology has been in use for some time in the field of space telescopes. It has been used to produce cost effective, replicated, light weight optics in the X-ray wave length. The aim of this paper is to give an overview of the process of nickel replication technology describing how it has been successfully applied to the space telescope field.

Developments in the technology for the next generation of ultra light weight X-ray optics will be described using actual results achieved and the testing that is in progress.

The technology and experience gained is currently being applied to other fields of astronomy encompassing wider ranges of wavelengths and much larger sizes. The electroforming makes use of replication is therefore ideally suited to production of many identical sections of a reflector that can then be assembled or deployed to form a much larger reflector. The production of such a reflector can then be achieved in a very cost effective way using proven space telescope technology

The technology required for in orbit assembly and optical alignment is under investigation for the next X-ray mission, XEUS, which will make use of groups of mirrors pre aligned before launch that will then be aligned together on a structure forming an aperture of 10m in diameter.

The experience of this technology to future generations of very large space telescope, in particular, infrared will be important.

2. REPLICATION BY ELECTROFORMING TECHNOLOGY

Nickel replication technology is the production of one or more objects by electroplating onto the surface of a master or mandrel. The layer of nickel deposited forms an exact copy of the surface that is then separated by an appropriate method to form an entirely new object. During the production process the master can also be coated with a variety of materials that are separated with the electroformed object during the release to form an integrally bonded reflective coating.

Replication technique by nickel electroforming has been in existence for a long time and in the past its ability to accurately replicate fine detail has been used for volume production of many diverse objects⁽¹⁾. Though many of these applications have been superseded by other production processes and yet more by new technology developments it is still one of the most effective technologies available to obtain thin, lightweight and very precise structures particularly in the field of optics, reflectors and wave guides.

A highly successful recent application of this technology has been for the production of X-ray mirrors for projects such as SAX and JET-X and XMM.

The first of these projects, SAX, involved the production of replicated double cone X-ray mirrors 300mm long and up to 300mm diameter. This was followed by JET-X⁽²⁾ the first application of the use of Wolter 1 (combined parabola-hyperbola) mandrels for replicated X-ray mirrors. Though the mandrels were of a similar diameter the use of the higher precision mandrel enabled further demonstration of the accuracy achievable by nickel replication. The technology was again progressed with the project XMM. Precision Wolter 1 mandrels up to 700mm diameter were used and through a sustained effort in the development of the process it was possible to better understand and therefore control the entire production process of the mirror shells^(3,4). The study concentrated in particular on the areas that lead to direct deformations of the mirrors such as internal stress during electroforming and the mechanical function of the release. The direct results of this technology development programme are apparent in the optical performance of the XMM project, as clearly illustrated in the performance of the mirror modules^(5,6,7) at 14.8-11.3 arcseconds half energy width measured at the Panter X-ray facility using 8keV well within the target figure of 22.0 arcsec⁽⁴⁾. The development process of the ultra thin mirror shells will be illustrated by comparison of mirror shells produced with the original XMM specification and the identical optical performance of mirrors with a 50% weight reduction.

The advancement of this technology in the application of X-ray mirrors has recently taken an interesting turn in that it has been applied to the production of reflectors and reflector panels. Though the process of electroforming has been used in the past for manufacturing parabolic reflectors these have been generally of low precision, high weight and used in applications such as solar concentrators and search light reflectors. During the X-ray projects, through developments in the field of process control, the technology has been brought to the level at which it is possible to produce a much larger range of structures to an accuracy that includes the range of infra red

3 APPLICATION OF THE TECHNOLOGY TO FUTURE X-RAY MISSIONS

Further development of the electroforming technology has indicated that these advances in the production techniques are not yet exploited to the limit. At MEDIA LARIO the one to one replication of the 5 arcsecond mandrels is the normal production quality for flight mirrors, however the practicality of making a further reduction in the weight of mirror shells has been demonstrated to the level where a 50% reduction in the design parameters of XMM have been achieved without degradation of the mirror optical quality ⁽⁸⁾. This corresponds to a mirror shell structure with a wall thickness of 0.2-0.5 mm from the smallest to the largest shell. The largest sizes of mirror shell have now been further reduced on a disproportional scale, thus demonstrating the possibility to produce large structures of optical quality with mean wall thickness of less than 0.25 mm (Mirror shell less than 2 Kg/m²).

The main characteristics of the ultra thin mirrors produced so far and the equivalent flight standard are illustrated in Table 1.

Table 1.

Mirror Type	Diameter mm	Wall thickness [microns]	MS weight as a % of XMM design	HEW by VOB [arcsec]
Flight	700	1070	96.1%	5.1
Development	700	500	50.2%	7.0
Development	700	260	24.8%	9.8
Flight	690	1050	97.1%	6.6
Development	690	500	50.5%	7.2
Development	690	258	24.5%	10.2
Flight	381	580	97.1%	5.9
Development	381	250	47.0%	5.4

Developments to increase the possible size of the such thin mirror shells are in progress and will confirm that the technology will be suitable to satisfy the requirements for any future X-Ray mission. The problem for this type of mirror design will come eventually with the limitations of the size of the launch vehicle.

For this purpose the production of development mirrors in sectors is in progress, Figure 1, and will eventually enable optics of an unlimited size to be assembled in orbit, Figure 2 illustrates electroformed dummy mirror sectors 0.3 mm in thickness. From the work already completed on mirror sectors it can be seen that although there is a clear structural advantage given by the closed shell design of the Wolter I used for previous missions, it is not essential to the production process, thin walled structures can be produced in other configurations.

This work forms part of the optics technology aspects of the feasibility study of XEUS telescope for which Media Lario is responsible. XEUS is a 10 m diameter X-ray observatory, figure 3, having Wolter I open surface mirrors nested in modular structures (petals), figure 4. The mirrors are typically 1m high and 1m wide with a thickness of the order 0.5mm, the nested structure then becomes approximately a 1m cube. The telescope at launch will have a reduced number of assembled petals and during its life time will dock with the International Space Station Alpha for the assembly of further petals to expand the available aperture and other refurbishment activities

The time scale of these activities are planned in the early part of the next decade and could provide a useful experience for the future activities and planned time scale first decade next century



Figure 1 Sector mirror 1000mm x 600mm in electroforming

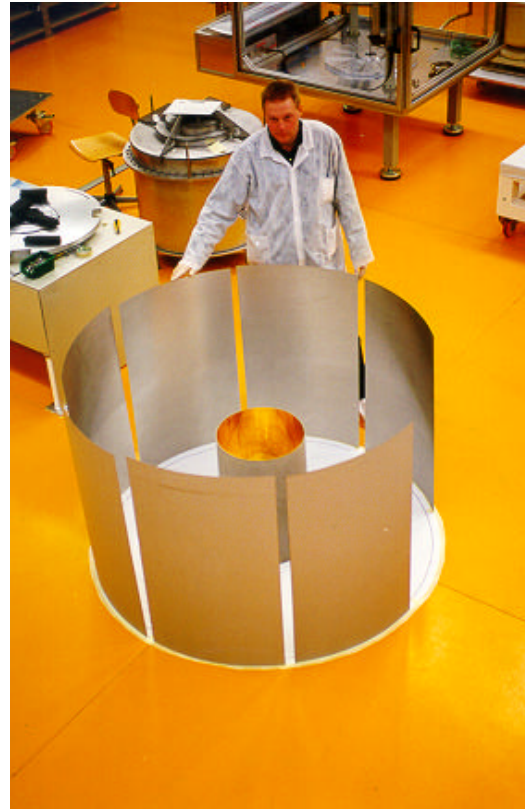


Figure 2, X-ray mirror configuration at 1500 mm diameter, XMM 400mm mirror to indicate scale

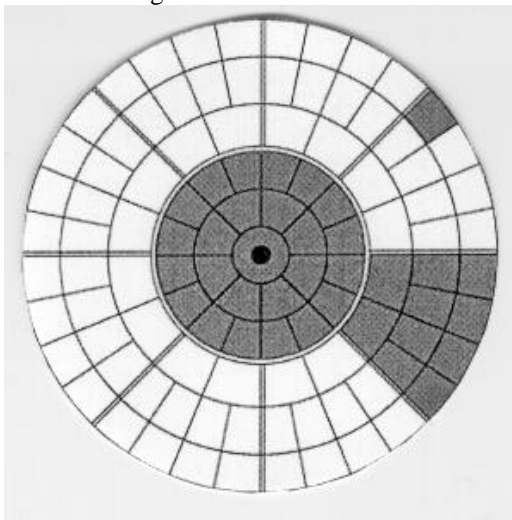


Figure 3 XEUS 10m aperture, showing launch configuration and build up concept

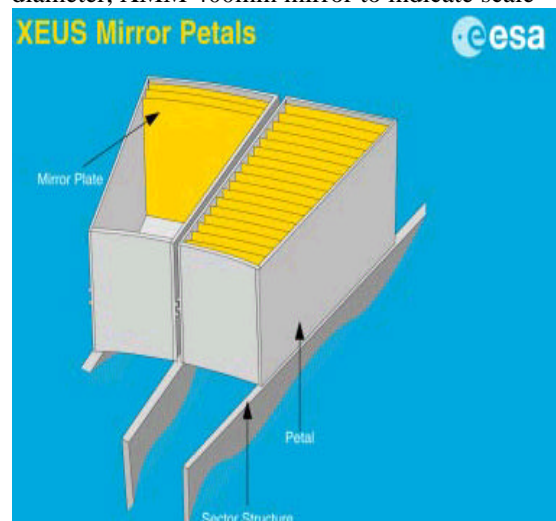


Figure 4, Mirror petal concept

This is of particular interest to this discussion in that it is a practical application of the requirement that future missions for any form of astronomy will need, the production of reflectors in component parts for later assembly or deployment in orbit

4 ELECTROFORMED MIRRORS OF ALTERNATIVE TYPES

The indirect results of development in thin walled technology have proven that the methods of production are equally applicable to other types of structures and mirrors. This can include open, essentially flat, structures such as sections of a larger parabolic reflector that can be assembled together to form a large antenna type of structure,

The precision of the electroformed skin produced in this process is extremely good, well into the optical range. The technique developed at Media Lario has now been to apply this technology to the available methods of support structure in such a manner as to produce a finished panel of the correct surface tolerance and physical characteristics for a wide range of purposes. In simple terms a trade off of weight against RMS shape and thermal performance. The precision achievable of a finished panel with this electroforming process can therefore be varied depending on the requirements of the application.

Production of a much higher precision nickel reflectors of a specification for infra red use is possible, however to maintain the system at a suitable weight it requires the reflective surface to be relatively thin for this level of precision and will therefore be flexible. The application of a suitable support structure is necessary, this does not however reduce the required performance of the reflector. From the considerable experience of nickel replication for X- ray optics, it is clear that the reflector must be produced in the optimum condition and then supported or integrated in a neutral manner to obtain the desired result

Rigid structures

For the purpose of antennas extremely light, rigid parabolic reflector panels, using a thin skin of nickel and an aluminium honeycomb core, have been produced at Media Lario, Figure 5. for use in Ka band communication antennas. The precision achievable of the electroformed skin is far in excess of the requirements for this application however the finished panel is “de-tuned” by the use of a lower precision, low cost master and a very light structure

Technology such as this is currently capable of producing reflectors that can be used in the sub millimetre and infra red range



Figure 5 Parabolic reflector produced using honeycomb support structure



Figure 6. Light weight secondary mirror demonstration model

An alternative method of rigid reinforcement is to use a light weight electroformed structure. Media Lario has produced various demonstration mirrors for the Secondary Mirror of SOFIA (Stratospheric Observatory for Infrared Astronomy) ⁽⁹⁾ in nickel having 355mm diameter and reaching a peak to valley of order of magnitude of 1µm, figure 6. The mirror was successfully vibration tested to 20g at 400Hz. The result of this experimental programme were determined to be dependent on the accuracy of the master which had a peak to valley of the order of magnitude of 1µm. Further analysis shows that the replication accuracy is significantly better than this.

Semi rigid and flexible

As an alternative to the process of making a mirror as a rigid self supporting structure it is possible to reinforce the reflective surface in a manner that it can be held in position using only a few points of contact and with a small number of actuators that are capable of removing the large scale deformations, such as astigmatism, and making the alignment.

This process can be continued to its extreme leaving only the membrane of the reflective surface supported by a suitable number of actuators and load spreaders.

This technology however provides a whole series of challenges for design, production and measurement that are familiar to the X-ray mirror replication process. The close packed nesting of the Wolter I mirror has always demanded the thinnest possible mirrors to maximise the effective area and as a consequence a considerable experience has been gained in the handling and measurement thin, very flexible mirrors. Detailed measurement, surface characterisation and integration of mirrors with a thickness of less than 0.5mm is normal procedure. For this process, though the measurement methods are quite standard, the method of supporting the mirror is most certainly not. The technique involves a series of shape optimisations using sophisticated suspension devices

The high volume of production possible from such a replication process, over 500 mirrors in three years for XMM, has also necessitated the development of measurement processes that enable a fast accurate estimate of mirror performance for production process control. Such types of measurement do not need to fully characterise the mirror performance, but when combined with the proper experience and understanding enable the production process to be optimised with a fast feed back of data.

Developments for the handling and measurement of large, flexible, long focal length parabolic sections are a challenging task that will be necessary for space telescope applications. Measurement using non contact methods and simulation of zero gravity will be necessary for membrane type reflectors.

Replication of this type is useful for the forming of high precision thin section mirrors. However, it also has an advantage in that once a precision manufactured tool has been produced, in a stable easily machined material, any number of replications is possible, XMM experience is up to 24 replications for X-ray 0.5 nm surface mandrels and almost unlimited at the surface finish required for infra red. The more that are produced, the lower the unit cost. This enables the production of off axis segments of a mirror that can then be assembled into a larger structure, an area of technology that will be critical to future missions.

There are many advantages in the use of metals for large reflectors such as the predictable thermal properties, isotropy, well characterised and predictable mechanical performance. This enables the manufacture of the reflector or reflector assembly to be done at one temperature whilst the operating conditions can be completely different and the performance calculated with a high degree of reliability.

Practical testing of the thermal properties of electroformed nickel from 400 to 140K has demonstrated linear variation of the coefficient of thermal expansion (CTE) in this range. Various samples were used to demonstrate good repeatability and isotropy. Extrapolation of this data to 40K gives a CTE of $3.6 \times 10^{-6} \text{K}^{-1(10)}$

5. SUMMARY

Production of mirrors and reflectors of various types has been demonstrated, these can be either in the form of thin membranes for use with a corrective actuator system, multiple flexures or rigid structure. The production parameters of the mirror can be optimised through the electroforming process and alloying to produce a structure with the correct characteristic for the varying types of applications.

The design of the mirror can be made in such a way as to allow many identical replications of a single master to be assembled to form a larger reflector thus improving cost effectiveness.

The necessary control of the production process is well understood, however the metrology methods for the measurement of such membranes and structures will provide the next major challenge.

The predictable surface characteristics and the ability to apply coatings during the electroforming process enables optimisation of the reflectivity for the required wavelengths.

The thermal properties of metallic mirrors enable the performance to be predicted at a wide range of temperatures with a high degree of reliability.

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